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Periodic Oscillations in the Intra-day Optical Light Curves of the Blazar S5 0716+714

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ABSTRACT

We present results of a periodicity search of 20 intra-day variable optical light curves of the blazar S5 0716+714, selected from a database of 102 light curves spanning over three years. We use a wavelet analysis technique along with a randomization test and find strong candidates for nearly periodic variations in eight light curves, with probabilities ranging from 95% to >99%. This is the first good evidence for periodic, or more-precisely, quasi-periodic, components in the optical intra-day variable light curves of any blazar. Such periodic flux changes support the idea that some active galactic nuclei variability, even in blazars, is based on accretion disk fluctuations or oscillations. These intra-day variability time scales are used to estimate that the central black hole of the blazar S5 0716+714 has a mass $> 2.5 \times 10^6$ $M_\odot$. As we did not find any correlations between the flux levels and intra-day variability time scales, it appears that more than one emission mechanism is at work in this blazar.

Subject headings: galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual (S5 0716+714)

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1. Introduction

Blazars are the subclass of radio-loud active galactic nuclei (AGNs) consisting of BL Lacertae objects (BL Lacs) and flat spectrum radio quasars (FSRQs). BL Lacs show largely featureless optical continua. All blazars exhibit strong flux variability on diverse time scales varying from a few minutes to many years at all accessible wavelengths of the electromagnetic spectrum. For convenience, blazar variability can be broadly divided into three classes, viz., intra-day or intra-night variability, short-term variability and long-term variability. Variations in flux of up to a few tenths of a magnitude over the course of a night or less is variously known as intra-day variability (IDV) (Wagner & Witzel 1995), which is the term we adopt here, microvariability (e.g., Miller, Carini & Goodrich 1989), or intra-night optical variability (e.g., Gopal-Krishna, Sagar & Wiita 1995) . Short- and long-term variabilities can amount to four or five magnitudes and are usually defined to have time scales from weeks to several months and several months to years, respectively.

It is widely accepted that the central engines of AGNs fundamentally are comprised of super massive black holes (SMBHs) along with the radiating matter accreting onto them. In the case of radio-loud AGN such as blazars, jets emerge from these central engines. IDV is most likely produced in close proximity to the SMBH (e.g., Miller et al. 1989), although an origin further away within a turbulent jet (e.g., Marscher, Gear & Travis 1992) is also possible. Minimum IDV time scales of blazars can be used to place constraints on sizes of the emitting regions, and, if the radiation is indeed emitted close to the center, on the masses of the SMBHs. Detection of periodic or quasi-periodic oscillations in optical IDV light curves of blazars would be strong evidence for the presence of a single dominant orbiting hot-spot on accretion disk, or accretion disk pulsation (e.g., Chakrabarti & Wiita 1993; Mangalam & Wiita 1993). Hence the search for periodic or quasi-periodic oscillations in the IDV light curves of blazars is of great interest; however, such variations have not yet been well established. The motivation of the present research program is to see if such periodic IDV patterns do indeed exist in the optical light curves of blazars.

For the present work, we extracted data from the published literature for optical IDV of the BL Lac object S5 0716+714. It is one of the brightest and therefore most well studied BL Lacs with respect to optical IDV. The optical continuum of this blazar is so featureless that many attempts made to determine its redshift have failed. The non-detection of its host galaxy allowed a lower limit to its redshift, $z > 0.3$ (Wagner et al. 1996), to be set and a later non-detection led to a claim that $z > 0.52$ (Sbarufatti, Treves & Falomo 2005). However, there has been a very recent claim of a host galaxy detection which produces a "standard candle" value of $z = 0.31 \pm 0.08$ (Nilsson et al. 2008). The duty cycle of the source is essentially unity, which implies that the source is always in at least a moderately active

state (Wagner & Witzel 1995). In the search for optical variability on diverse time scales in this source, it has been observed intensely over at least the last 15 years (e.g. Wagner & Witzel 1995; Wagner et al. 1996; Heidt & Wagner 1996; Ghisellini et al. 1997; Sagar et al. 1999; Villata et al. 2000; Qian, Tau & Fan 2002; Raiteri et al. 2003; Wu et al. 2005, 2007; Nesci et al. 2005; Stalin et al. 2006; Gu et al. 2006; Montagni et al. 2006; Ostorero et al. 2006; Foschini et al. 2006; Villata et al. 2008; Gupta et al. 2008 and references therein). Five major optical outbursts were reported for this source; they occurred at the beginning of 1995, in late 1997, in the fall of 2001, in March 2004 and in the beginning of 2007 (Raiteri et al. 2003; Foschini et al. 2006; Gupta et al. 2008). These five outbursts indicate a timescale of long-term variability of $\sim 3.0 \pm 0.3$ years (e.g., Raiteri et al. 2003). Correlated radio/optical short-term variability measured over a month seemed to reveal some quasi-periodicities for this blazar (Quirrenbach et al. 1991; Wagner et al. 1996).

This paper is structured as follows. In §2 we discuss the source of the data we use and we describe the criteria employed to select the light curves for this study. In §3 we describe the wavelet analysis and randomization technique we employ in our analysis. Our results are presented in §4 and we discuss them and draw conclusions in §5.

2. Data and Selection Criteria

There have been several attempts to search for optical IDV in the blazar S5 0716+714 over the last decade or so, and a few of the most comprehensive studies are by Sagar et al. (1999); Wu et al. (2005, 2007); Montagni et al. (2006); Stalin et al. (2006); Pollock et al. (2007); and Gupta et al. (2008). While examining these papers, we found that the best quality data, in the sense of having a combination of the longest nightly durations, the best time resolution, and nearly uniform sampling, was published by Montagni et al. (2006).

We downloaded the Montagni et al. (2006) data on 0716+714 taken on 102 nights between 1999 and 2003 from the SIMBAD astronomical database[1]. We visually inspected all of these light curves (LCs) to decide which might be most suitable for a periodicity search.

First we rejected the 37 LCs that had observational gaps during that night. Next, the 5 LCs that had median errors more than 0.015 mag. were rejected so as to obtain a high quality data set. For the remaining 60 LCs we obtained the intra-day variability amplitude, A, defined as (Heidt & Wagner 1996)

$$A = 100 \times \sqrt{(A_{max} - A_{min})^2 - 2\sigma^2} \ \%, \qquad (1)$$

[1]http://simbad.u-strasbf.fr/simbad/

where A_{max} and A_{min} are the maximum and minimum magnitudes in the calibrated LC of the blazar and σ is the averaged measurement error of that blazar LC. So as to obtain LCs for which the presence of IDV is unquestionable, we only tentatively accepted the 30 LCs with $A > 10\%$. Finally, we rejected the 10 LCs with data extending over less than 7.5 hours.

This entire set of selection criteria were satisfied on 20 nights for which the LCs extend from 7.7 to 12.3 hours. The dates, filters used, LC durations and variability amplitudes for these selected datasets are given in the first four columns of Table 1.

3. Wavelet Analysis and Randomization Technique

We use a wavelet plus randomization technique, which has certain advantages over the commonly used periodogram and Fourier power spectra approaches in searching for statistically significant real periodicities in IDV LCs. The wavelet analysis computer code "randomlet" was developed by E. O'Shea in the environment of IDL (Interactive Data Language) software (O'Shea et al. 2001). Using this code, we can find statistically significant real periodicities (if they exist) in time series data. The program incorporates a randomization test as an additional feature to the standard wavelet analysis code of Torrence & Compo (1998) which allows robust non-parametric estimates of the probabilities that periodic components contribute to a signal (e.g., Bradley 1968).

Details of the randomization technique used to examine the existence of statistically significant real oscillation periods were given by Linnell Nemec & Nemec (1985) for investigations of stellar pulsation periods and by O'Shea et al. (2001) in the context of solar coronal variability. This technique has led to several important results in the context of solar physics by analyzing approximately uniformly sampled data (e.g., Banerjee et al. 2001; O'Shea et al. 2001, 2005; Ugarte-Urra et al. 2004; Popescu et al. 2005; Srivastava et al. 2008a,b). A similar technique was used by Mathioudakis et al. (2006) in searching for periodic variations in the active star EQ PegB.

Here we use this tool for the first time to search for periodicity in blazar optical IDV data that are also approximately uniformly sampled. We note that there have been previous efforts to study other types of blazar variability using variants of the wavelet technique. For example, Kelly et al. (2003) used a continuous wavelet transform and cross-wavelet analysis to search for long time scale variations in the multi-band radio LCs of 30 AGN; they found a quasi-periodic variability in at least one of the radio frequencies at which these AGN were monitored for a majority of them. Examination of the radio variability of PKS B0048−097 with the same technique found a quasi-period of $\sim$ 460 days that later was replaced by a

more precise period of $\sim$ 585 days (Kadler et al. 2006). A wavelet analysis of 19 X-ray LCs from 10 AGNs recently led to the claim of the presence of a 3.3 ks quasi-period in one data train from the quasar 3C 273 (Espaillat et al. 2008). The "randomlet" approach gives an easily understood way to employ wavelets along with a well-established statistical test for the reality of claimed periodicities in the time series data of the blazar 0716+714.

In all wavelet analyses, the search for periodicities in light curves is carried out through a time localized function that is continuous in both frequency and time. The wavelet used in this study is the Morlet function which is defined as

$$\psi_t(s) = \pi^{-1/4} \exp(i\omega t) \exp\left(\frac{-t^2}{2s^2}\right) , \tag{2}$$

where t, s, ω and $\pi^{-1/4}$ are the time parameter, wavelet scale, oscillation frequency parameter, and the normalization constant, respectively. A Morlet function involves the product of a sine wave with a Gaussian envelope. The non-dimensional oscillation frequency parameter (ω) is set equal to 6 in order to satisfy the admissibility condition (Farge 1992). The Fourier period P is related to the wavelet scale s in the Morlet function by the simple relation, $P = 1.03s$.

The wavelet is convolved with the time series to determine the contribution of that frequency to the time series through matching the sinusoidal portion by varying the scale of the wavelet function. This method produces the power spectrum of the oscillations in different light curves. We note that the Morlet wavelet suffers from an "edge effect" that is typical of analyses of time series data. Fortunately, this effect is only significant in regions that are within a cone of influence (COI) that demarks where possible periods that are too close to either the measurement interval or the maximum length of the time series cannot be convincingly detected. The wavelet procedure, its noise filtering capabilities, and the impact of COI effects are described in detail in Torrence & Compo (1998).

The randomlet software obtains measurements of the peak power in the global wavelet spectrum, which is the average peak power over time, and is equivalent to a smoothed Fourier power spectrum. In principle, the randomization technique compares the average values of the actual time series to the peak powers evaluated for $n!$ equally-likely permutations of the time series data, using the assumption that the n values of measured intensities are independent of the n measured times if no periodic signal is present. The fraction of permutations that provide peak values greater than or equal to the original peak power of the time series provides the probability (p) that there is no periodic component. Thus the acceptance percentage probability that real periodic components are present in the data is $(1 - p) \times 100$. To claim a statistically significant oscillation period is present the lowest acceptance probability we allow is 95%, although it might be better to call these candidate

periodicities. We consider really firm detections to have acceptance probabilities of $\geq 99\%$.

Because computing $n!$ permutations is computationally very expensive, we calculate $m = 200$ permutations. This allows a reliable estimation of p, as the 95% confidence interval for the true value of p is $p \pm 2[p(1-p)/m]^{1/2}$ (Linnell Nemec & Nemec 1985). The estimated value of p can have a value of zero, i.e., there is an almost zero chance that the observed time series oscillations could have occurred by chance. In this case, the 95% confidence interval can be obtained using the binomial distribution and is given by $0.0 < p < 0.01$, that is, the probability of a real period having been found is 99−100 % (O'Shea et al. 2001).

Since the blazar data are also approximately uniformly sampled we can use O'Shea's code to produce the power spectra of the IDV on different nights. It should be noted that there is no time gap in any of the chosen data sequences. We use an average smoothing technique, based on low-pass filtering methods, to reduce noise in the original signal before searching for possible real periodicities. This is accomplished through the "running average" process in O'Shea's wavelet tool that smooths the original signal by a defined scalar width, taken to be 10. This process uses the "smooth" subroutine available with the IDL tool kit which returns a copy of the array smoothed with a boxcar average of the specified width. The smoothed signal is then subtracted from the original signal to yield the resultant signal used for the wavelet analysis.

4. Results

4.1. Wavelet Analysis Results for IDV Time Scales

We used high quality optical IDV data of the blazar S5 0716+714 taken on 20 nights during the period November 26, 1999 to March 23, 2003 from Montagni et al. (2006). The data were available as magnitudes vs time. We converted them into fluxes vs time and then performed the wavelet analysis along with a randomization test described in §2 on these 20 IDV LCs to search for periodicities and IDV time scales for each light curve.

The LCs, plotted so as to show fractional deviations of intensities from the nightly means, are given for several of the nights in the upper-left panels of Figs. 1−4. The wavelet power transforms of those LC are shown in the middle-left panels of Figs. 1−4 while the dates the data were taken are given in the captions. Here we have plotted the wavelet analysis results of the three out of the 20 nights during which the probability a period (or quasi-period) is really present is 99−100%, as well as that for one night during which such a signal was much weaker (Fig. 4). In the middle-left panels of these figures the darkest regions show the most enhanced oscillatory power. The cross-hatched areas are the cone of influence

(COI), the region of the power spectrum where edge effects, due to the finite lengths of the time series, are likely to dominate. Because of this COI the maximum possibly detectable periods range between 10 and 16 ks for different nights.

In our wavelet analyses, we consider time scales that correspond to the highest power peaks, that lie below those COI thresholds and have full-night probability estimates above 95% to be have high significance and thus provide good period candidates. The middle-right panels in the figures show the global wavelet power spectra of the LC time series from which those periods can be selected. The width of those peaks indicate that they are better characterized as quasi-periods in most cases. We use the term quasi-period here in the sense of Espaillat et al. (2008), i.e., the nominal period is not crisply defined, as can be seen most clearly in Figs. 1 and 3; however, these signals do not really resemble the QPOs seen in X-ray binaries (e.g., Remillard & McClintock 2006), and so, to avoid confusion with them we will henceforth just use the word "period".

Finally, the bottom-left panels show the probabilities of the presence of two specific frequencies corresponding to the first and second highest peaks shown in the middle-right panels as functions of the time after the start of the observations that night. The numbers quoted for those periods at the bottom-right of these figures give the maximum values of the probabilities and not the global probability level given at the upper-right. The solid line represents the probability corresponding to the major power peak of time series data, while the dotted line corresponds to the secondary power peak. Note that the major power peak shows very high probabilities for extended intervals during the night, while the secondary peaks never do so for more than a short period. We only consider the period corresponding to the first major power peak in our analysis.

The wavelet analysis results for IDV time scales (or oscillation periods for a portion of the flux) and their probabilities are given in columns 5 and 6, respectively, of Table 1 for all 20 nights that satisfied the selection criteria discussed in §3. We have only presented in Figs. 1–3 the wavelet analysis results for the LCs which have the highest probability (99−100%) of the existence of statistically significant time scales. For the sake of comparison, in Fig. 4 we have also presented the wavelet analysis result of a LC in which we did not find any dominating and statistically significant time scale. From the intensity wavelet spectrum of Fig. 1, we found that the first oscillation period of $\sim$3.2 ks dominates over the $\sim$ 50–300 min span, while the second oscillation period of $\sim$5.0 ks dominates over the $\sim$ 300 – 500 min portion of the time series but not as strongly as did the first one. In the global wavelet spectrum, which is an average of the wavelet spectrum over time (Torrence & Compo 1998; O'Shea et al. 2001), the period corresponding to the maximum power is $\sim$3.2 ks. It is also clear from Fig. 2 that a period near 4.3 ks is present in the whole night's time series and

always dominates outside the COI. In Fig. 3 we see that a period of $\sim$1.9 ks is nearly always present and is very strong between $\sim$100 and 300 minutes and again after 400 minutes that night.

4.2. Black Hole Mass Estimation

The mass of the central black hole (BH) in an AGN is probably the single most important quantity to be known about its central engine. The more reliable, or primary, black hole mass estimation methods include stellar and gas kinematics, reverberation mapping and megamaser kinematics (e.g., Vestergaard 2004). The stellar and gas kinematics methods require high spatial resolution spectroscopy of the host galaxy, the reverberation mapping method requires detection of higher-ionization emission lines from gas close to the BH, and megamasers, when present, are only detectable in essentially edge-on sources. Since the optical spectrum of the blazar 0716+714 is a featureless continuum it is not possible to determine the black hole mass using the methods that require spectroscopy; and, as blazars are nearly face-on sources, the megamaser technique is also moot. Secondary black hole mass estimation methods are either approximations to the reverberation mapping approach that still rely on the presence of a well measured strong emission line or they employ well-known empirical relations between the black hole mass and the velocity dispersion or mass of the host galaxy's bulge. The marginal detection of the host of 0716+714 (Nilsson et al. 2008) means that these approaches to the value of its BH mass are also not useful in this case.

Variability time scales can also provide estimates of the mass of an AGN's BH. An observed variability doubling time, Δt_{obs}, provides a crude bound on the mass if the changing flux arises in the accretion flow close to the BH. One could then use causality to limit the size of the emitting region to $R \leq c\Delta t_{obs}$. Combining this result with the expectation that the minimum size for such an emitting region is fairly closely related to the gravitational radius of the BH, $R \geq R_g \equiv GM/c^2$ (e.g., Wiita 1985) one can obtain an estimate for M. But if the source of the variable blazar emission is instead from the jet and moving at a velocity v (e.g., Marscher & Gear 1985) then the intrinsic doubling time in the rest frame of the blazar flow, Δt_{in}, is given by $\Delta t_{in} = [\delta/(1+z)]\Delta t_{obs}$, where $\delta = [\Gamma(1-\beta\cos\theta)]^{-1}$ is the Doppler factor, with $\beta = v/c$, $\Gamma = (1-\beta^2)^{-1/2}$ and θ is the viewing angle to the jet axis. For typical blazars, $\delta \sim 10$, albeit with a substantial range (e.g., Ghisellini et al. 1998). Earlier measurements of the Lorentz factor for this source from ejection velocities of radio knots showed a decrease in the apparent superluminal speeds from $\sim 15c$ to $\sim 5c$ over the course of a decade (Bach et al. 2005). Those changes are consistent with a constant $\Gamma \simeq 12$ but a decreasing value of θ from 5° to $0^\circ.5$ during that period, leading to a rise in δ from

$\sim$ 13 to $\sim$ 25 (Montagni et al. 2006). However, it must be stressed that even when knot motions can be determined by VLBI measurements, obtaining an accurate value of δ is very difficult, particularly if the jet has a finite opening angle (e.g., Gopal-Krishna, Dhurde & Wiita 2004).

In the case where an apparent periodic (or nearly periodic) signal is found, as appears to be the case for 0716+714, then there is some hope to be able to do better with mass estimates. In these circumstances, it is probably most reasonable to assume that the period is related to the orbital timescale of a blob or flare in the inner portion of the accretion disk (e.g., Mangalam & Wiita 1993). The minimum likely period then corresponds to the orbital period at the inner edge of the accretion disk, which is usually taken to be given by the marginally stable orbit, R_{ms}, although it is conceivable that emission can occur from matter at even smaller radii (e.g., Abramowicz & Nobili 1982). For a non-rotating (Schwarzschild) BH, $R_{ms} = 6GM/c^2 = 6R_g$, while for a maximal Kerr BH, with angular momentum parameter $a \rightarrow 1$, $R_{ms} \rightarrow R_g$. However, for a more realistic maximum angular momentum parameter of $a = 0.9982$ then $R_{ms} \simeq 1.2R_g$ (e.g., Espaillat et al. 2008).

The angular velocity of co-rotating matter orbiting a BH, as measured by an inertial observer at infinity is given by (e.g., Lightman et al. 1975)

$$\Omega = \frac{M^{1/2}}{r^{3/2} + aM^{1/2}} \ , \tag{3}$$

where geometrical units, $G = c = 1$, have been used, and $r = R/R_g$. This leads to an expression for the BH mass in terms of the observed period, P, in seconds,

$$\frac{M}{M_\odot} = \frac{3.23 \times 10^4 \ P}{(r^{3/2} + a)(1 + z)}. \tag{4}$$

The nominal masses obtained in this fashion for a Schwarzschild BH (with $r = 6$ and $a = 0$) are column 7 of Table 1, and those obtained for a maximal Kerr BH (with $r = 1.2$ and $a = 0.9982$) are in column 8. If the periodic perturbations in the inner part of the disk are advected into the jet and the observed emission comes from a relativistic flow directly affected by those perturbations then the value of M would require the results obtained from Eq. (4) to be multiplied by δ, so these mass estimates are really lower bounds.

4.3. Correlation between Flux and IDV Time Scale

In our sample of 20 clearly variable IDV LCs, 16 were measured in the R band but 4 were taken using a V filter. Those V band measurements have to be converted to R in order

to investigate any correlation between the flux level and quasi-periodic variation. Sagar et al. (1999) reported an average V−R color of this BL Lac to be ~ 0.4 mag. in their one month long BVRI optical monitoring campaign in 1994. We adopted this value of V−R and converted the V magnitudes of the four LCs into R magnitudes and then calculated average nightly fluxes in the R band for them. We also computed the average fluxes of the 16 nights where the LCs are already in the R band.

In Fig. 5 we plot the average nightly flux vs highest probability IDV time scales (P), noting however, that some of the timescales have rather low probabilities of being real. We see that there is no correlation between the average flux and the IDV time scales of the blazar, regardless of whether all 20 points or the 5 with the highest probabilities are considered. It is worth noting that the most confident periods are only detected on nights when the total flux is high. This is reasonable if larger mean fluxes correspond to times when the periodic variable component is stronger.

These 20 nights were spread over more than 3 years (November 26, 1999 to March 23, 2003). Since the source has shown long-term quasi-periodicity on the time scale of 3.0 ± 0.3 years (Gupta et al. 2008), this blazar has gone through most, if not all, of its (so-far observed) long-term states during the period in which the data for the present work was obtained. It is generally believed that in the pre-outburst, outburst and post-outburst states, even the optical emission can be attributed to the shock moving down the inhomogeneous medium in the jet (e.g., Marscher et al. 1992). On the other hand, in the low state of a blazar, IDV arising from instabilities in the accretion disk could more easily be detected (e.g., Mangalam & Wiita 1993).

In blazars, the radiation emitted by the plasma in the jet, which has bulk relativistic motion and is oriented at small viewing angles, will be affected by relativistic beaming, which in turn implies a shortening of the observed timescales by a factor of δ^{-1}. A correlation between average flux and IDV time scales should be expected if the variability arises from changes in the velocity of, and/or viewing angle to, the emitting region. We do not see such a correlation, which implies that optical emission from this blazar is not governed by this single mechanism and thus that more than one source of the radiation is probably present at these times.

5. Discussion and Conclusion

There are two major classes of models for AGN variability, those involving shocks-in-jets and those invoking instabilities on or above accretion disks. The former is expected to

dominate in blazars and the latter is most important when jets are absent or weak (e.g., Wagner & Witzel 1995; Urry & Padovani 1995; Mangalam & Wiita 1993). In another jet-based variant it is argued that for low-luminosity AGNs, the accretion disk is radiatively inefficient and any small amplitude variation, even in the low-state of the source, will be due to a weak jet (e.g., Chiaberge et al. 1999, 2006; Capetti et al. 2007, and references therein). This variant may be able to explain optical IDV in blazars. The detection of quasi-periodicity or periodicity on IDV time scales can be most easily explained by the presence of a single dominating hot-spot on the accretion disk (e.g., Mangalam & Wiita 1993; Chakrabarti & Wiita 1993) or perhaps by pulsational modes in the disk (e.g., Espaillat et al. 2008).

Together, the difficulties in obtaining lengthy, high quality, and essentially evenly spaced data for ground based observations of AGN, and the weaknesses of the standard analysis tools (periodograms and Fourier transforms) under these circumstances, has meant that performing good searches for periods or quasi-periods in blazars has been difficult until recently. So it is not surprising that there have been few strong claims of quasi-periodic variations in blazar LCs. Carini et al. (1992) noted a weak peak in the power spectrum of optical IDV observations of OJ 287 at ≈ 32 minutes, but it was not statistically significant. In the same blazar, Carrasco et al. (1985) earlier claimed periodic variations on timescales of tens of minutes but they were not convincing. Earlier excellent optical data of the blazar 0716+714 has shown possible quasi-periodicity on the timescales of ~ 1 day, 4 days and 7 days, and some of these were in apparent synchrony with radio variations, but the time series were too short to provide conclusive evidence (Wagner 1992; Heidt & Wagner 1996). Very recently, using X-ray data for the blazar 3C 273, Espaillat et al. (2008) have reported quasi-periodicity on a timescale of 3.3 ks. If these fluctuations represent orbital periods they would imply central BH masses for 3C 273 some 10 to 100 times smaller than independent determinations have found, so Espaillat et al. (2008) favor the hypothesis that the variations they have seen arise from higher-order modes within the disk. To our knowledge, no other members of the blazar class have shown significant harmonic components in the IDV or short-time scale LCs.

Here we have used a wavelet plus randomization technique (Linnell Nemec & Nemec 1985; O'Shea et al. 2001) to search for optical IDV time scales of the blazar S5 0716+714. We selected 20 nights of IDV data that were characterized by long strings of approximately uniformly sampled data with high IDV signals and low noise from an initial database of 102 nights of observations by Montagni et al. (2006).

We found high probabilities ($\geq 95\%$) of (at least quasi-) periodic oscillations in eight of these IDV LCs and very high probabilities ($\geq 99\%$) for five of them. This is the first evidence of detection of periodic components in blazar optical IDV LCs. We found quasi-periodic IDV

time scales between $\sim$ 25 and $\sim$ 73 minutes.

These variability timescales lead to nominal BH masses ranging from 2.47 – 7.35 $\times$ 10^6 $M_\odot$ assuming the period arises from a Schwarzschild BH, while for a rapidly rotating Kerr BH these mass estimates rise to 1.57 – 4.67 $\times$ 10^7 $M_\odot$. However, if these variations arise from internal disk modes then the corresponding BH mass can be substantially larger, by factors of $\sim$10 to over 100. And if they do emerge from an inner portion of the jet where they are induced by disk fluctuations, the masses would be increased by a factor of $\delta \sim 20$; however, if they emerge from jets at large distances from the SMBH, then clearly no information on the BH mass can be extracted from these timescales.

We did not find any correlation between average flux and IDV time scales, which implies that optical emission from the blazar is probably not governed by a single mechanism. Our results appear to be most consistent with models in which accretion disk variability plays a role in the optical emission of blazars. Nonetheless, it is possible that emission from turbulet jet, which is also precessing or swinging (e.g., Camenzind & Krockenberger 1992; Gopal-Krishna & Wiita 1992) could also explain these observations.

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Table 1. Wavelet analyses for IDV of the blazar S5 0716+714

Date (dd.mm.yyyy)	Band	Duration (hours)	Amplitude (%)	Time Scale (seconds)	Probability (%)	BH Mass (Sch.) (10^6 $M_\odot$)	BH Mass (Kerr) (10^7 $M_\odot$)
26.11.1999	V	11.34	36	4295	95.0	7.21	4.58
12.01.2000	V	11.40	32	3205	82.0	5.38	3.42
25.01.2000	V	10.74	32	3301	92.0	5.54	3.52
27.10.2000	V	7.72	19	1473	99.0	2.47	1.57
14.02.2001	R	10.55	11	1978	92.5	3.32	2.11
26.02.2001	R	10.00	29	2050	96.0	3.44	2.19
03.11.2001	R	10.04	15	1670	90.5	2.80	1.78
01.02.2002	R	8.19	12	3039	91.5	5.10	3.24
13.03.2002	R	8.77	10	3530	30.0	5.92	3.76
15.03.2002	R	9.23	14	3004	58.5	5.04	3.20
20.03.2002	R	9.32	10	2415	93.5	4.05	2.57
25.03.2002	R	9.36	18	3226	99−100	5.41	3.44
22.04.2002	R	7.68	22	4298	99−100	7.21	4.58
29.12.2002	R	12.25	53	1917	95.0	3.22	2.04
18.02.2003	R	10.92	21	3759	94.0	6.31	4.01
04.03.2003	R	9.40	39	2041	83.0	3.42	2.18
18.03.2003	R	8.63	15	1890	99−100	3.17	2.01
23.03.2003	R	9.16	24	4380	99.5	7.35	4.67

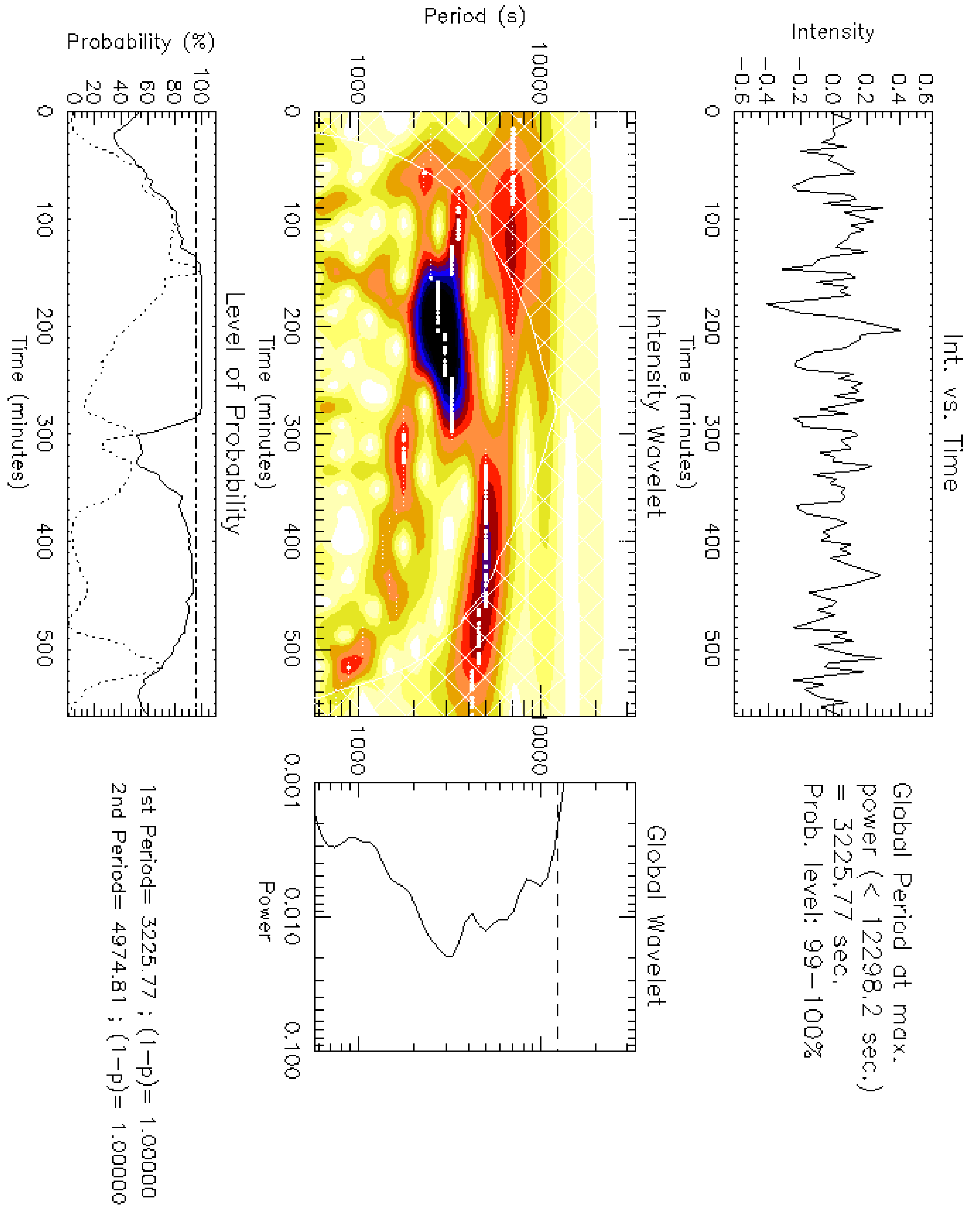

Fig. 1.— Wavelet analysis for the light curve of the blazar S5 0716+714 for the date March 25, 2002. The top panel shows the variation of fluxes computed from the data of Montagni et al. (2006) with the overall most significant period described at the top right. The wavelet power spectrum is given in the middle panels, with the shortest scales at the bottom. The

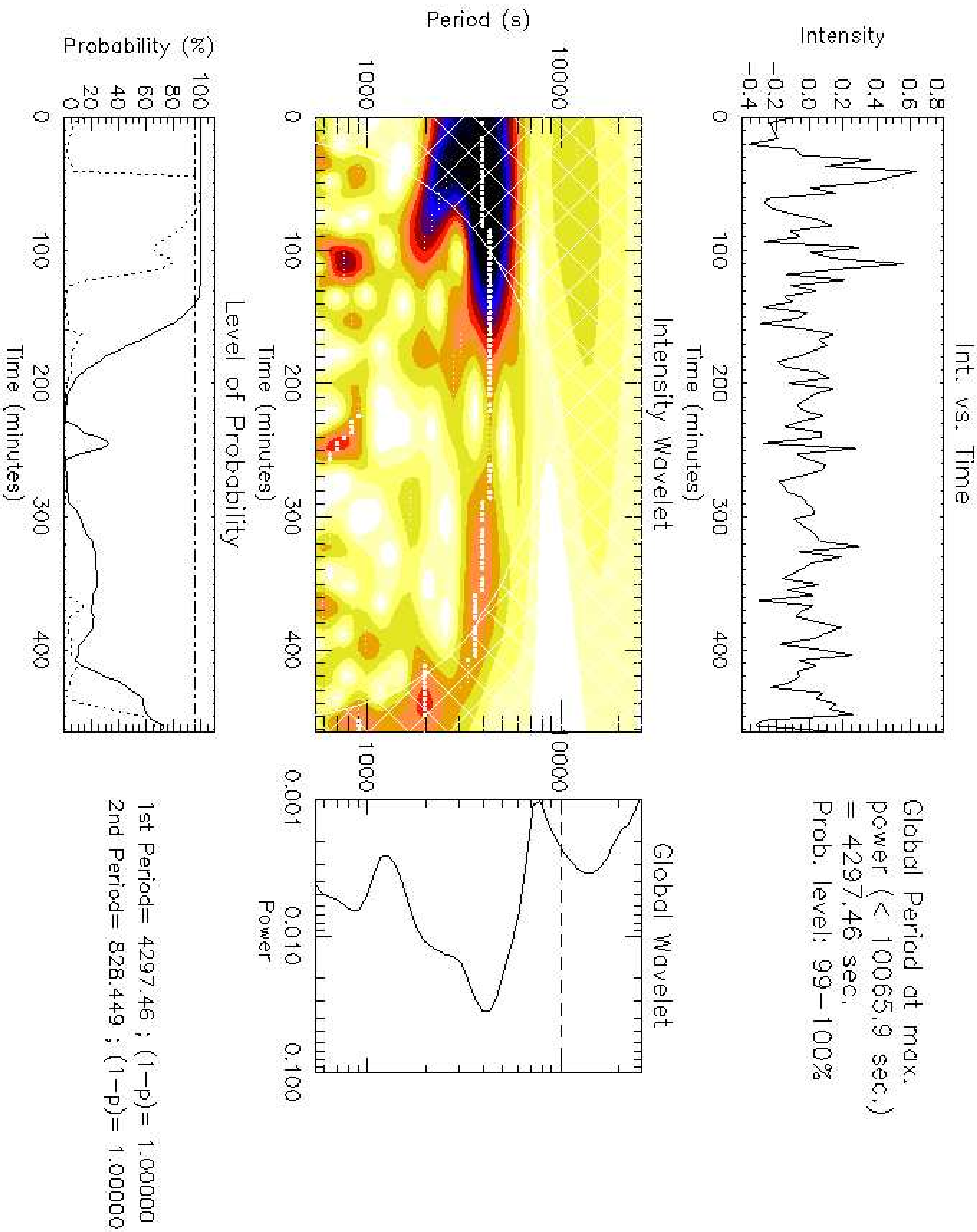

Fig. 2.— As in Fig. 1 for April 22, 2002.

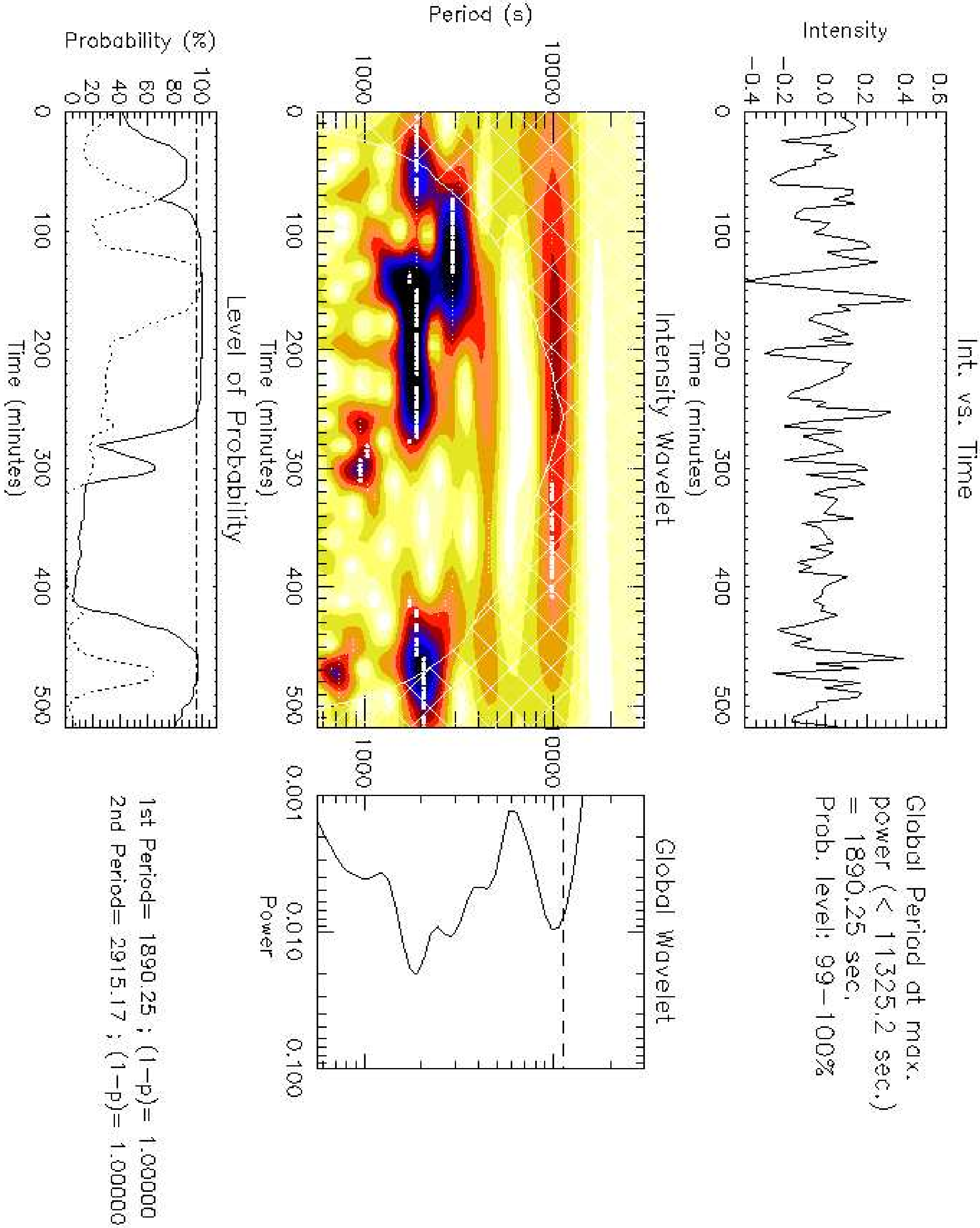

Fig. 3.— As in Fig. 1 for March 18, 2003.

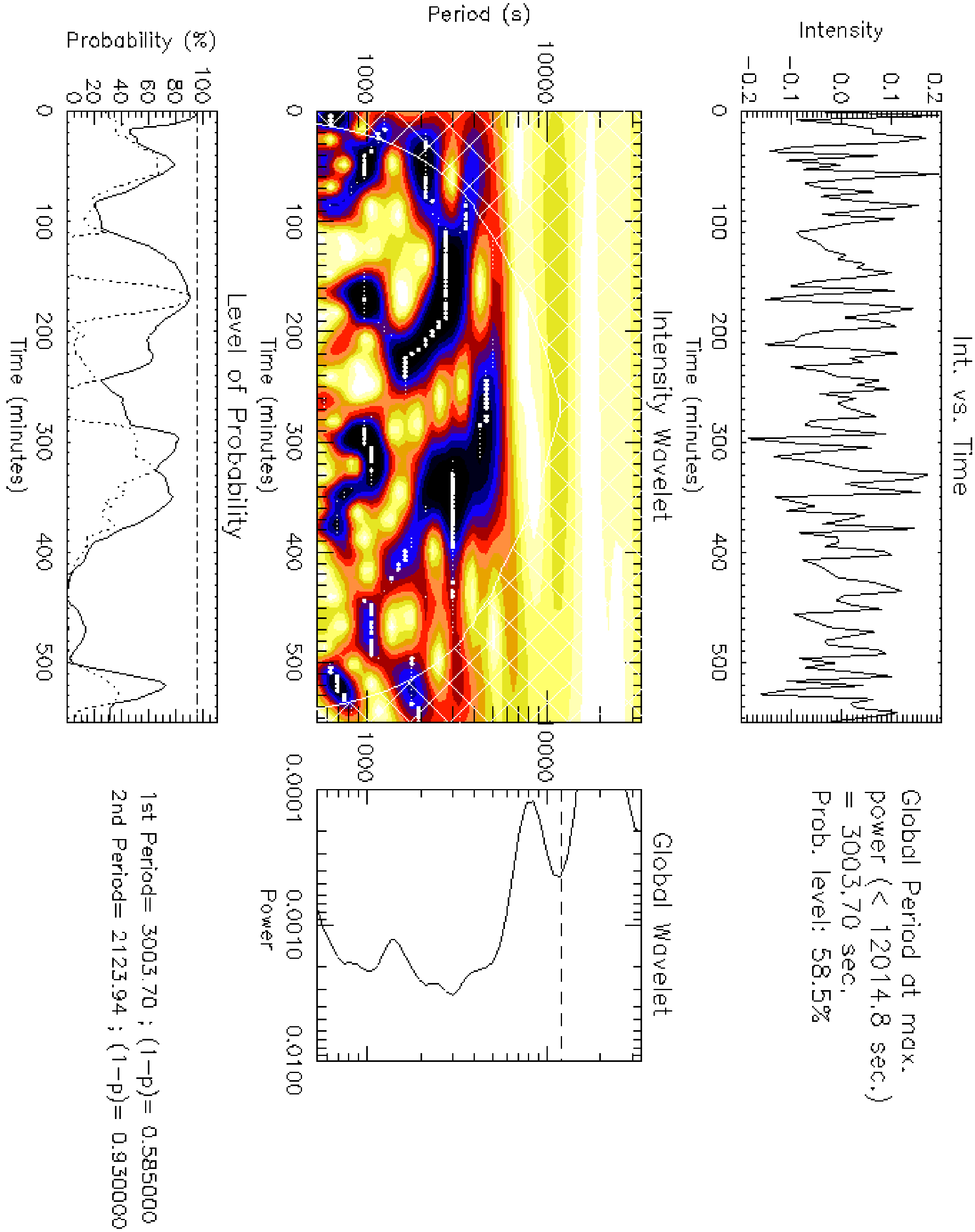

Fig. 4.— As in Fig. 1 for March 15, 2002.

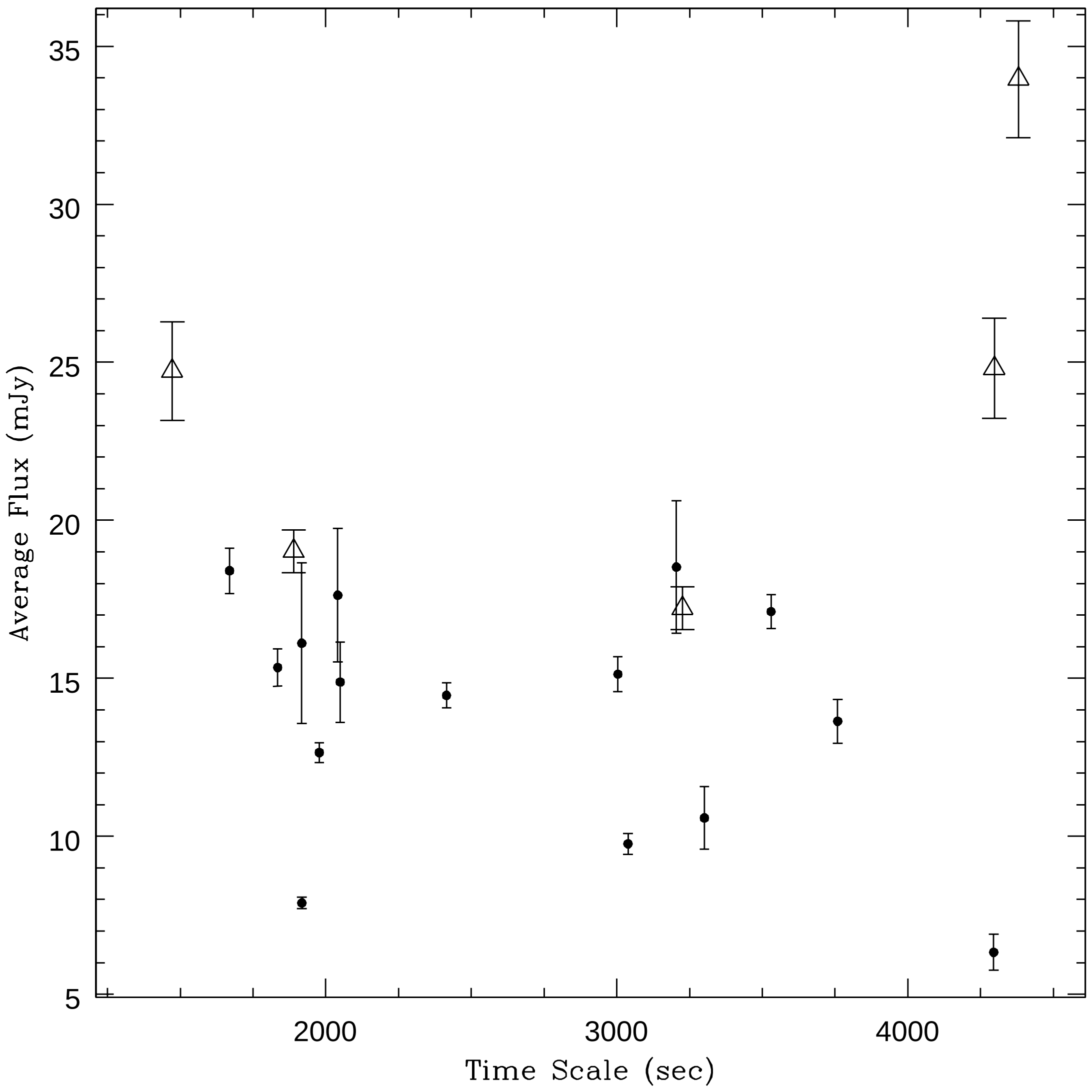

Fig. 5.— Average nightly R band flux vs IDV timescale for the sample of 20 LCs given in Table 1. Open triangles indicate that the probability of detection of a periodic component in the variability is $\geq 99\%$.